Technical Letter Report

Three-Stage Target Rock Safety Relief Valve Performance and Reliability in Long-Term Station Blackout Accident Scenario for State of the Art Reactor Consequence (SOARCA) Program

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Executive Summary

An independent analysis of the performance and reliability of a three-stage Target Rock safety relief valve in a Long-term Station Blackout (LTSBO) scenario for a Boiling Water Reactor (BWR)-4 with Mark I containment is presented. This analysis is quantitatively compared to the corresponding evaluation of this component included in a State of the Art Reactor Consequence Analysis (SOARCA) analysis [1] applied to the Peach Bottom nuclear power plant. In the current document, a detailed three-dimensional finite element analysis of major components of the valve is performed, with convective heat transfer from the main steam system applied. The analyses show reasonable agreement with the SRV stem to guide gap closure analysis (corresponding to valve seizure) presented in the SOARCA report. The time to valve seizure in the open position is estimated to be between 4,100 and 4,600 seconds (after the initial 10 hours of the LTSBO event) at a corresponding steam line temperature of approximately 800 to 900 K. The SOARCA report calculates valve seizure due to material degradation at a valve stem temperature of 900 K, corresponding to a main steam line temperature of 950 K. The result is that there is a difference in steam line temperature at failure calculated in the SOARCA report of 950 K and the maximum steam line temperature at valve failure of 900 K calculated in the current report. Sensitivity studies have been performed in SOARCA [1] that conservatively bound this temperature difference, and therefore this difference is believed to provide no deviation from the conclusions presented in SOARCA.

Separately, the SRV's stochastic failure to re-close is discussed. The expected value for the number of valve cycles to failure (270) used in the SOARCA study [1] is found to be reasonable. Additional physical basis for this value is provided in the current report.

1. Introduction

The U.S. NRC's State of the Art Reactor Consequence Analysis (SOARCA) program has been developed to provide a more realistic, best-estimate evaluation of potential accident consequences at commercial U.S. reactors [1]. Lead by the Office of Nuclear Regulatory Research's Division of Systems Analysis (RES/DSA), SOARCA consists of analyses of various accident scenarios ultimately affecting the major barriers to fission product release. Site-specific weather and population data are used to determine the effects on public health and safety. In the first phase of SOARCA, the Peach Bottom Nuclear Generating Station BWR and Surry pressurized water reactors (PWR) were chosen for the study. The licensees for both plants volunteered to participate in the SOARCA program.

Among the BWR accident scenarios considered within SOARCA is a Long-term Station Blackout (LTSBO), where all alternating current sources are unavailable. In this case, the remaining operable active equipment include the turbine-driven reactor core isolation cooling (RCIC) pump and three-stage Target Rock SRV. Throughout this scenario, the SRVs cycle many times, relieving reactor coolant system (RCS) pressure and exhausting steam via a tailpipe to the torus. By passing steam at elevated temperatures, the SRVs and their internals will heat up, expand, and potentially fail by seizing in either the open or closed position.

The SOARCA report [1] focuses on three potential failure modes in evaluating the performance and reliability of SRVs in a LTSBO; including i) stochastic failure, ii) differential thermal expansion, and iii) material deformation due to decrease in strength of the constituent materials with an increase in temperature. Pilot valve failure and spring softening are mentioned as possible failure mechanisms but not addressed in detail in the SOARCA report.

RES/DSA requested RES Division of Engineering (RES/DE) to independently analyze SRV performance in the LTSBO scenario, and provide an estimate of the time at which an SRV will fail via thermal seizure. This report contains an analysis of the performance and reliability of major SRV components in this scenario, including estimates of how and when the valve will fail. The analysis is completed using the finite element program ABAQUS [2], with convective heat transfer input taken from the associated thermal-hydraulic calculations documented in the SOARCA report [1]. The SRV failure time and mode is used in the SOARCA program to analyze accident progression and consequences.

In addition, estimates of SRV stochastic failure, i.e. independent of the LTSBO transient, are discussed. This failure probability is used in the aleatory uncertainty analysis portion of SOARCA.

2. SRV Operation

2.1 LTSBO Heat Removal Flow Path

In a LTSBO scenario for a BWR-4 with Mark I containment (representative of the Peach Bottom Nuclear Generating Station) steam from the top of the reactor vessel flows through the RCIC turbine that drives a pump taking suction from the torus and discharging back into the vessel. This flow path allows decay heat from the reactor core to be transferred to the cooler torus water. The main steam and feedwater line isolation valves are closed, thereby isolating the RCS. Note that BWR-4/Mark I designs typically have between 12 to 14 SRVs connected to main steam lines. Upon reaching a high pressure setpoint of approximately 7.58 MPa (1100 psi), or when commanded by a reactor operator, an SRV will lift to relieve RCS pressure by discharging steam via a tailpipe to the torus.

2.2 Automatic Valve Operation

Figure 1 shows a conceptual diagram of a two-stage Target Rock SRV in the closed position. To clarify the nomenclature, the first stage for this valve is the pilot mechanism, and the second stage is the main valve disk assembly. While the following discussion describes the operation of a two-stage SRV, the operating principles between this valve and a three-stage valve are similar, with the exception being that the three-stage valve includes an intermediate (second) stage, and the main valve disk assembly is the third stage. The operation of the pilot mechanism and main valve components are effectively identical.

Under normal power operation conditions, RCS steam pressure enters the valve from the inlet side and drywell pressure exists on the outlet side. This significant differential pressure is the driving force that maintains the main valve disk in the closed position. Referring to Figure 1, RCS steam pressure propagates from the valve inlet to the following spaces:

- the left side of the pilot valve via the pilot sensing port
- past the volume containing the stabilizer disk to the open volume containing the main valve preload spring (i.e. the space above the main valve piston)
- the open space beneath the main valve piston

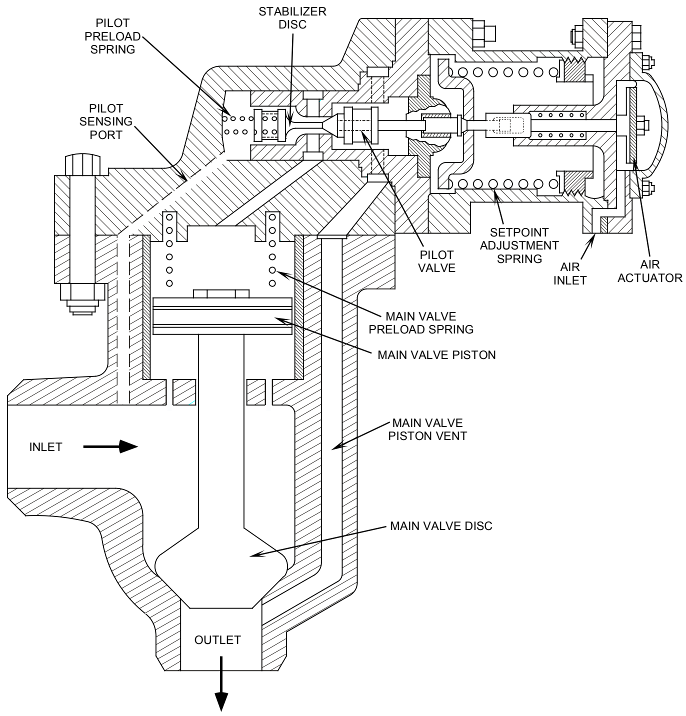

Figure 1. Two-stage Target Rock SRV in the closed position (courtesy U.S. NRC Technical Training Center)

The key details associated with the valve in the *closed* position are i) that RCS pressure exists above and below the main valve piston, resulting in no differential pressure across the piston, ii) a large differential pressure exists across the main valve disk, creating a large seating force, and iii) the pilot mechanism is held closed by the setpoint adjustment spring pushing the pilot valve disk against its corresponding seat.

Increasing RCS pressure will create additional force on the pilot valve. Upon reaching the valve's setpoint, the pilot valve will open (Figure 2) venting the open space above the main valve piston via the main valve piston vent to the downstream (outlet) side of the valve. A large differential pressure will now exist across the main valve piston, similar to the differential pressure existing across the main valve disk. However, the main valve piston has a larger diameter than the main valve disk, resulting in a net upward force on the disk / stem / piston assembly. With the main valve disk open, RCS pressure is free to depressurize by venting directly from the inlet to the outlet nozzle of the valve.

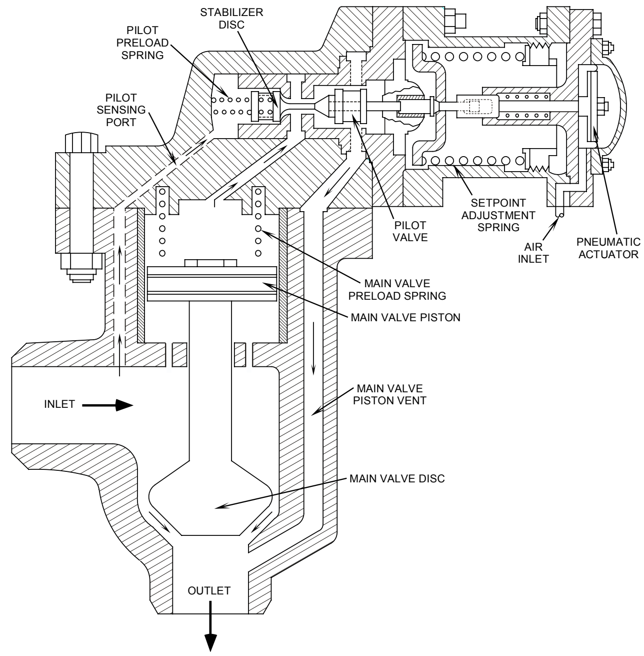

Figure 2. Two-stage Target Rock SRV in the open position (courtesy U.S. NRC Technical Training Center)

The main valve preload spring is sized to push the disk / stem / piston assembly downward to the closed position when the differential pressure across the main valve piston is approximately 0.34 MPa (50 psi). This will allow the setpoint adjustment spring to push the pilot valve closed, thus returning the SRV to the closed position.

Note that leak tightness between the pilot mechanism disk and seat can be difficult to achieve under ideal conditions. Industry operational experience has shown seat leakage to have occurred in some cases [3]. Once the valve has been opened and closed under operating conditions, pilot leak tightness cannot be assured. However, at normal operating temperature and pressure conditions, the pilot mechanism will likely hold sufficient pressure for the main valve components to re-seat. In addition, setpoint drift has also been observed in some plants [4].

3. SRV Failure Modes in LTSBO

As mentioned above, in a LTSBO for a BWR 4 with Mark I containment, SRVs are assumed operable at the start of the event to provide RCS over-pressure control. Analyses have shown [1] that, in the first ten hours of this transient, the SRVs will cycle open and closed approximately 440 times. During each cycle, the valves open approximately every 45 seconds, and remain open for approximately four to six seconds. After ten hours of the LTSBO, thermal-hydraulic calculations show that the heat removal capacity of the wetwell is effectively exhausted (since the residual heat removal system is unavailable), and RCS temperature will rise. RCS pressure will also continue to increase, resulting in additional open demands on the SRVs with increasing steam temperature.

Given this extreme temperature excursion beyond valve design conditions, several failure modes are possible. Clearly, temperature increase will give rise to thermal expansion of the SRV, resulting in potential binding of internal components. The valve is fabricated from several different materials with unique thermal expansion coefficients and temperature dependent properties including stiffness, strength and strain hardening. Other potential failure modes include, but are not limited to:

- Main valve spring fatigue failure following several hundred SRV operations.
- Corrosion binding, wherein corrosion products accumulate on tight seating surfaces. This would likely cause the valve to fail closed, requiring additional pressure beyond setpoint to open the valve.
- Steam cutting in the pilot mechanism. This would likely take more time to occur than analyzed in the LTSBO. The pilot mechanism will likely leak after the first lift, but the main valve disk can be expected to re-seat.

In addition, for any mechanical component, there is an inherently random probability of failure. For the SRV, this can be failure to open or close at any point in an accident scenario. A study of this phenomenon has been conducted by Idaho National Engineering Laboratory [5], in which a great deal of industry data involving valve failures has been compiled without delving deeply into the underlying mechanical causes for such failure. There is an underlying cause for all valve failures; however, in many cases, determining the precise cause may be prohibitively difficult. Hence, for probabilistic studies such as SOARCA, an entirely random, stochastic failure model is needed to quantify component reliability information which is aleatory.

The latest version of the SOARCA report [1] focuses on the following potential failure modes in evaluating the performance and reliability of SRVs in a LTSBO:

1. Stochastic failure as described above
2. Differential thermal expansion, including i) the effects of different material properties (particularly the difference in thermal expansion coefficient between the stainless steel stem and the carbon steel guide surrounding the stem) and ii) effects of temperature gradient within the valve body given that major components within the valve will heat up at different rates
3. Material deformation due to decrease in strength of the constituent materials with an increase in temperature

Pilot valve failure and spring softening are mentioned as possible failure mechanisms but not addressed in detail in the SOARCA report.

To supplement the information contained in the SOARCA report, an evaluation of the SRV in a LTSBO is presented in this report. The analysis is conducted using the finite element analysis code ABAQUS [2]. Major components of the SRV are modeled, including the body and disk / stem / piston assembly. The goal of this analysis is to provide an independent evaluation of the failure modes in items 2 and 3 above, using consistent basic accident scenario assumptions, but with a different analysis technique than that used in the SOARCA program. Finally, supplemental information is provided regarding the stochastic failure model described in item 1.

4. Thermal Transient Failure Analysis

In the LTSBO accident scenario, an SRV will cycle open and closed many times to relieve RCS pressure. In each cycle, the SRV is open for approximately four to six seconds, and closed for approximately 45 seconds [1]. Therefore, during the course of the event, approximately 90% of the time is spent with the valve in the closed position with no steam flow through the valve; in the remaining 10% of the time the valve is open, passing high temperature steam. Although the majority of the event time is spent with the valve closed, the majority of steam heat is transferred to the valve via convection while the valve is open. It is postulated that, while in the open position, the valve will reach a temperature at which the stem has increased in diameter to a greater extent than the surrounding guide, and fail to re-close due to interference between the stem and guide. In summary, while the bulk of the LTSBO time is spent with the valve closed, the bulk of the heat transfer (and associated thermal expansion) occurs with the valve open. For this reason, it is assumed that, if the valve fails due to thermal expansion, it will be stuck open. The SOARCA project [1], and its associated thermal-hydraulic codes, require as input the time at which the SRV will fail. Therefore, the goal of this analysis is to predict the time at which the SRV main valve stem diameter has increased to the point where the gap between the stem and guide has decreased to zero.

4.1 Finite Element Analysis

The SRV finite element model geometry is shown in Figure 3. Only the major portions of the valve are modeled, including the valve body with inlet and outlet nozzles, main valve disk / stem / piston assembly, guide, seat, and main valve spring. For efficiency, all components except the main valve spring are modeled with half symmetry. The finite element geometry is based on an assembly diagram from the valve manufacturer [6]. Assuming that the inlet nozzle inner diameter is 6" and the outlet nozzle is 10", the original diagram is imported into ABAQUS CAE [2], traced in Sketch mode, and scaled to obtain the appropriate dimensions. Note the difference in mesh densities in the valve seat and guide locations relative to their surrounding material. To simplify the meshing procedure and provide additional accuracy in these regions, the guide and seat portions of the model are generated separately and thermally and mechanically coupled via the ABAQUS "tie" command [2].

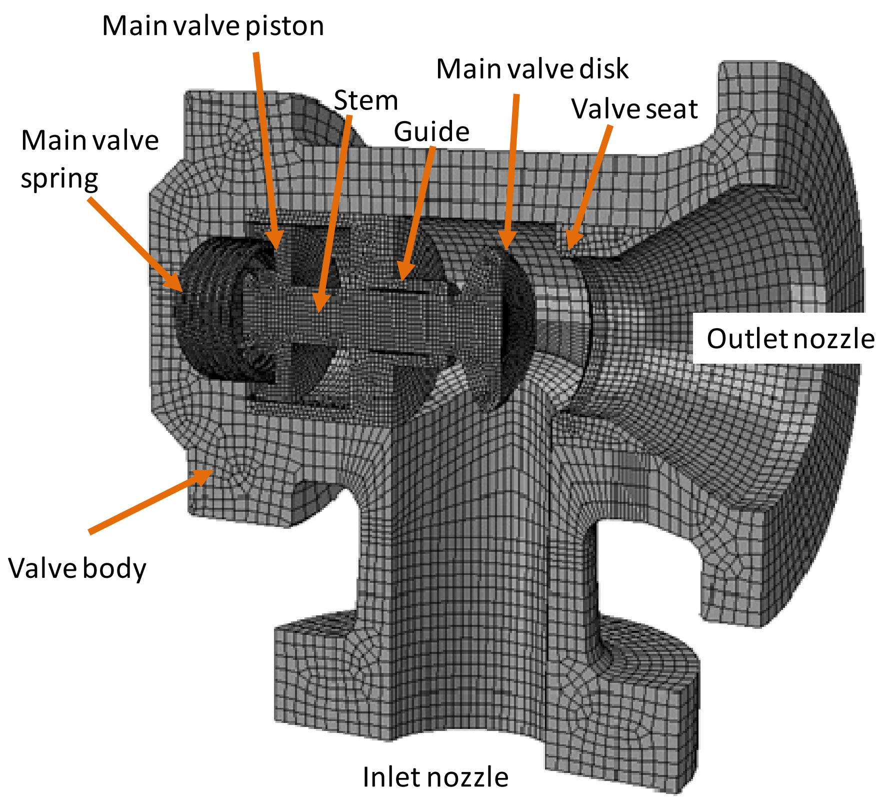

Figure 3. SRV finite element model

The materials used in the valve are extracted from a drawing from the valve manufacturer [7], and are listed in Table 1. Figures 6 through 8 show the elastic modulus, true stress vs. true strain, and thermal expansion coefficients as functions of temperature. Note that the properties assumed for Inconel correspond to alloy 82/182, as opposed to the actual X-750 used in valve construction. Since the main valve spring does not contribute to the gap closure analysis, this difference is negligible in the current analysis.

Table 1. Materials of Construction used in SRV

SRV Component	Material
Main body, including guide and seat	Carbon Steel (ASTM-A-216-WCB)
Main valve disk/stem/piston	T-304-L Stainless Steel (ASTM-A-182F)
Main spring	Inconel X-750 (AMS-5699)

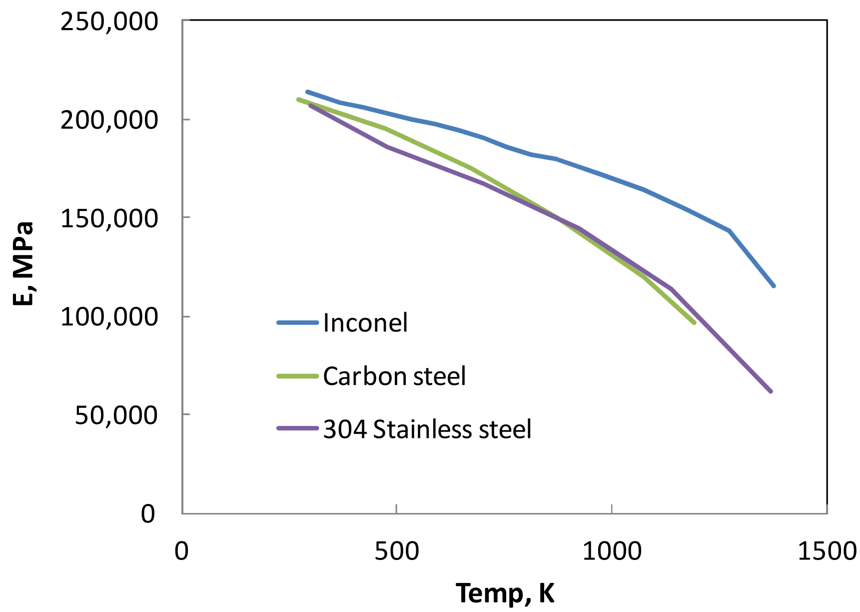

Figure 4. Elastic modulus vs. temperature for Inconel, Carbon steel and 304 stainless steel

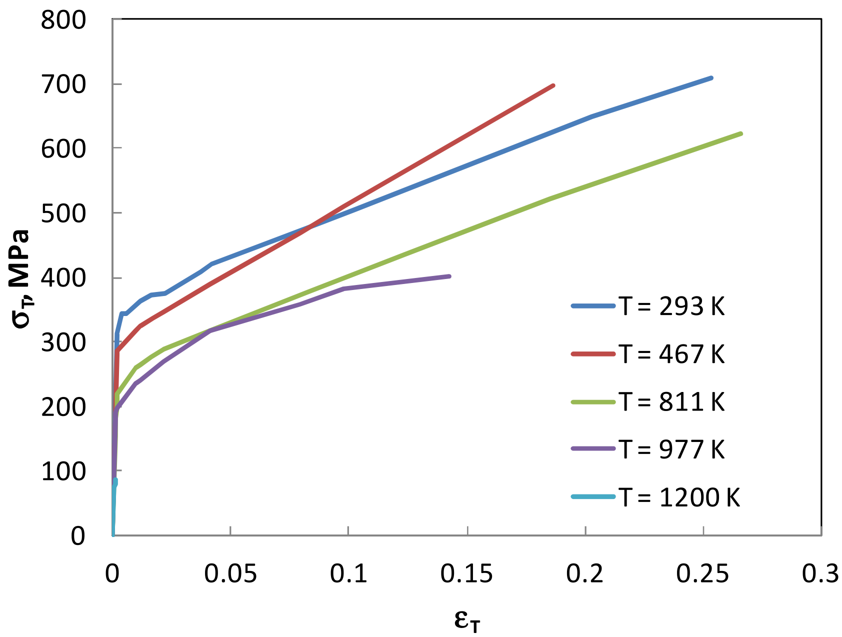

Figure 5. True stress vs. true strain at various temperatures for Inconel

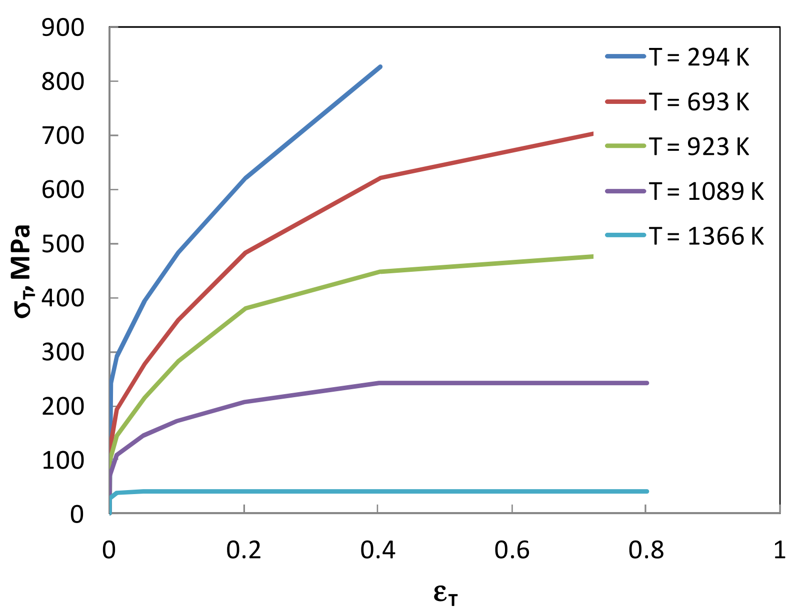

Figure 6. True stress vs. true strain at various temperatures for 304 stainless steel

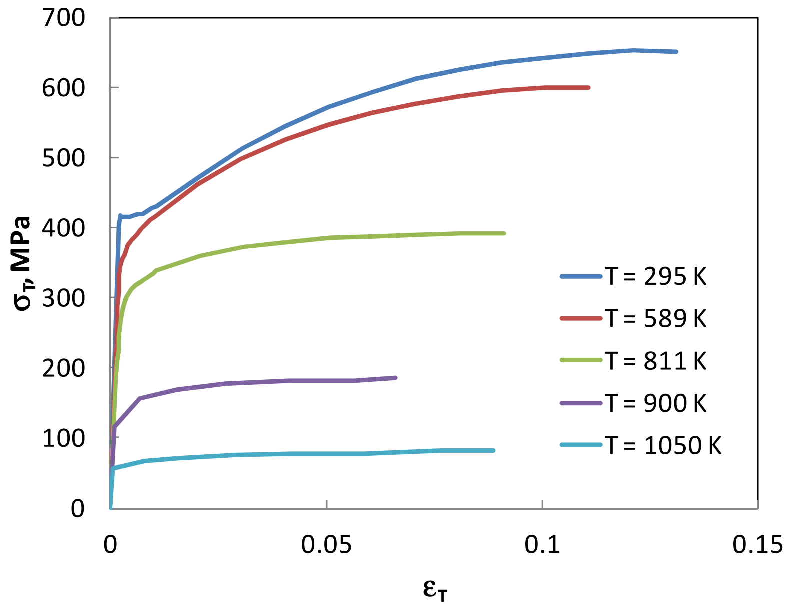

Figure 7. True stress vs. true strain at various temperatures for carbon steel

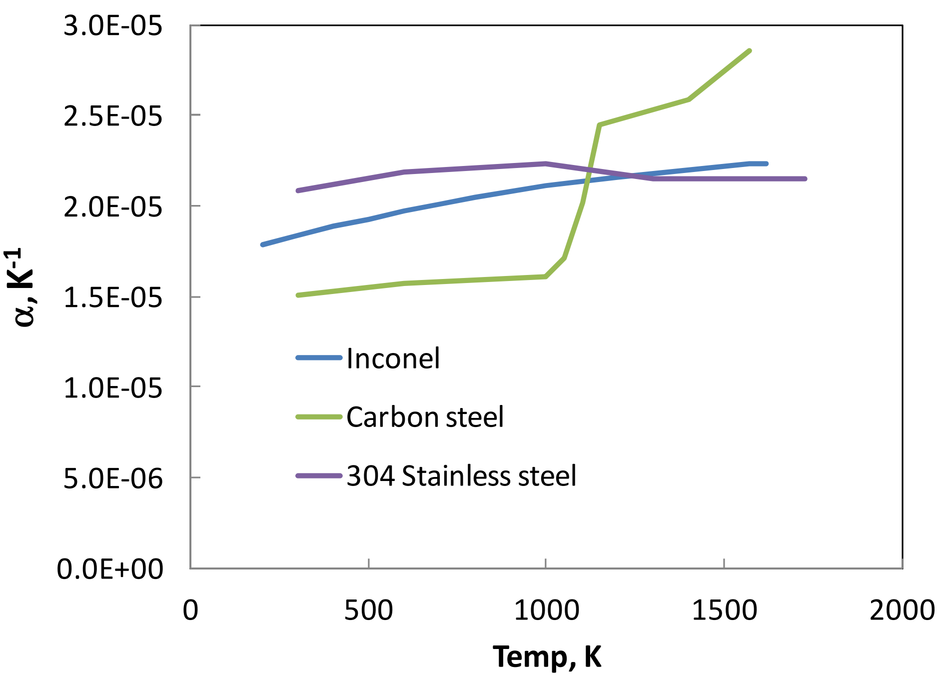

Figure 8. Thermal expansion coefficient vs. temperature for Inconel, Carbon steel and 304 stainless steel

4.2 Finite element model features

In service, the SRV is insulated, therefore, the outer surface of the valve finite element model is treated as adiabatic, i.e. no heat is transferred via convection or conduction from the outer surface of the valve. Given the temperature range considered, radiation heat transfer is not expected to significantly affect the results, and is therefore not considered at any point in the analysis. At the beginning of the finite element analysis, all valve components have an initial temperature of 560 K imposed, corresponding approximately to normal operating temperature. It is assumed that piping attached to the valve inlet and outlet nozzles would experience the same temperature transient as the valve itself, so heat transfer across the flat nozzle outer surfaces is also neglected. In operation, heat is transferred to the valve entirely through convection from steam passing through the valve. In the finite element model, for each of the solid valve components, heat is transferred internally through conduction with thermal conductivity parameters appropriate to each material type. Figure 9 shows the finite element model internal surfaces that are in contact with steam that receive heat transfer via convection. Based on data from the SOARCA report [1], a convective heat transfer coefficient of 850 W/m^2-K is used to model heat energy transferred from steam passing through the valve. For steam passing from the inlet nozzle, through the open space surrounding the valve disk and exiting through the outlet nozzle, the full convective heat transfer coefficient of 850 W/m^2-K is assumed. By necessity of valve operation, a portion of steam flowing through the valve is ported into the open space surrounding the main valve piston, main valve spring and adjacent portion of the main valve stem. The magnitude of this steam flow is unknown, but is a fraction of that flowing through the main portion of the valve. To account for the uncertainty associated with this fractional flow re-distribution, a sensitivity study is performed wherein the convective heat transfer coefficient in this region of the valve is varied at values of 5, 10 and 20% of the full value that is applied to the main portion of the valve.

The BWR LTSBO accident scenario analyzed in the SOARCA report evolves over a period of time. Approximately 600 minutes following accident initiation, the drywell heat removal capacity is exhausted, and the RCS will begin to heat up. The current analysis begins after this initial 600 minute period and evaluates the valve performance during the following 100 minutes (6000 seconds). Figure 10 provides main steam line gas temperature as a function of time, where time equal to zero corresponds to 600 minutes following accident initiation. This data is taken directly from the SOARCA report [1] and, for reference, is also provided in Table 2. The temperature-time history of Figure 10 and Table 2 are used as the sink temperature in the current finite element analysis. For efficiency, the finite element calculation is completed as a coupled thermal-displacement analysis, eliminating the need to map thermal results to the structural analysis. As discussed above, the SRV cycles open and closed many times during a LTSBO event. Each time the valve is opened, the SRV receives a pulse of thermal and mechanical energy from the steam passing through it. As a simplifying assumption, the dynamic nature of these pulses is neglected by applying the temperature time history of Figure 10 to the finite element model as continuous convection heat transfer. In reality, the pulses of increasing temperature would ratchet up the valve temperature incrementally.

Regarding mechanical boundary conditions, the flat outer surfaces of the inlet and outlet nozzles are assumed to remain in-plane. Referring to Figure 11, the outlet nozzle outer surface is free to translate in the x-z plane, but not in the y-direction, and the inlet nozzle outer surface is free to translate in the y-z plane, but not in the x-direction. The z-plane forms a symmetry plane for all modeled components except the main valve spring.

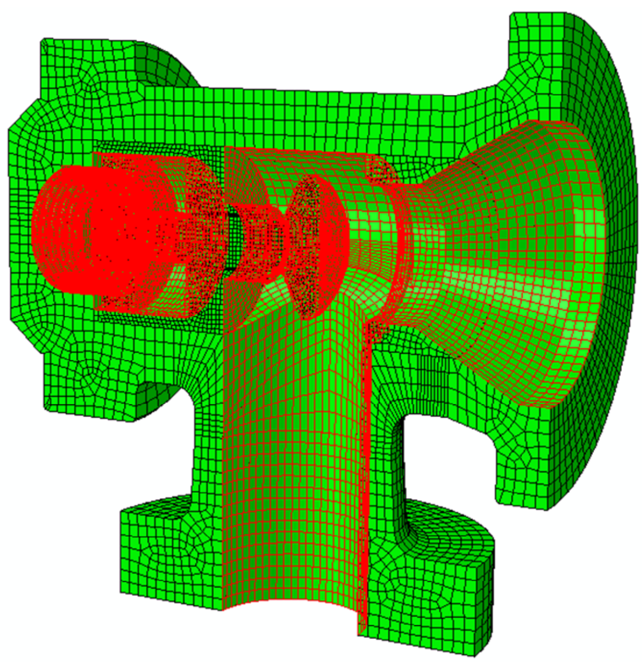

Figure 9. Surface definitions for convective heat transfer

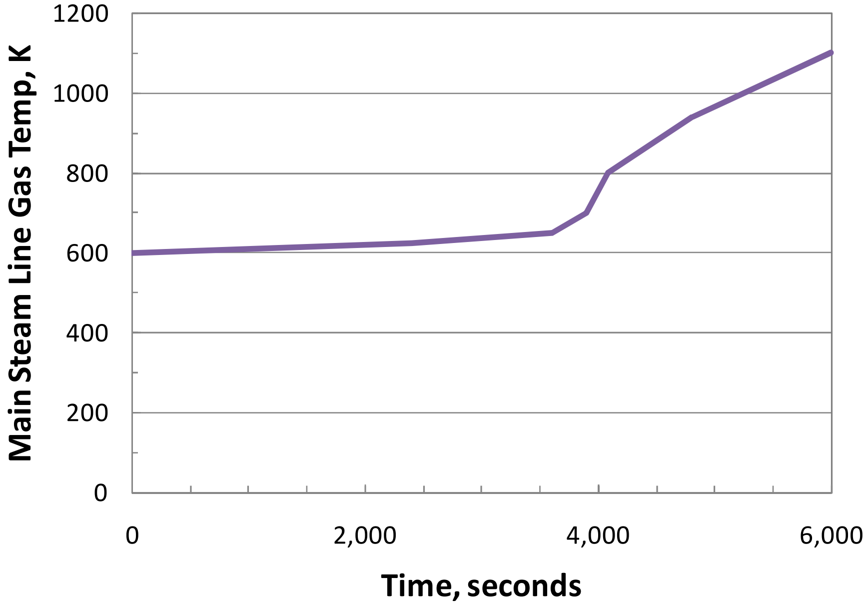

Figure 10. Main steam line temperature vs. time

Table 2. Main steam line gas temperature vs. time [1]

Time (sec)	Main Steam Line Average Temperature (K)
0	600
2400	625
3600	650
3900	700
4080	800
4800	940
6000	1100

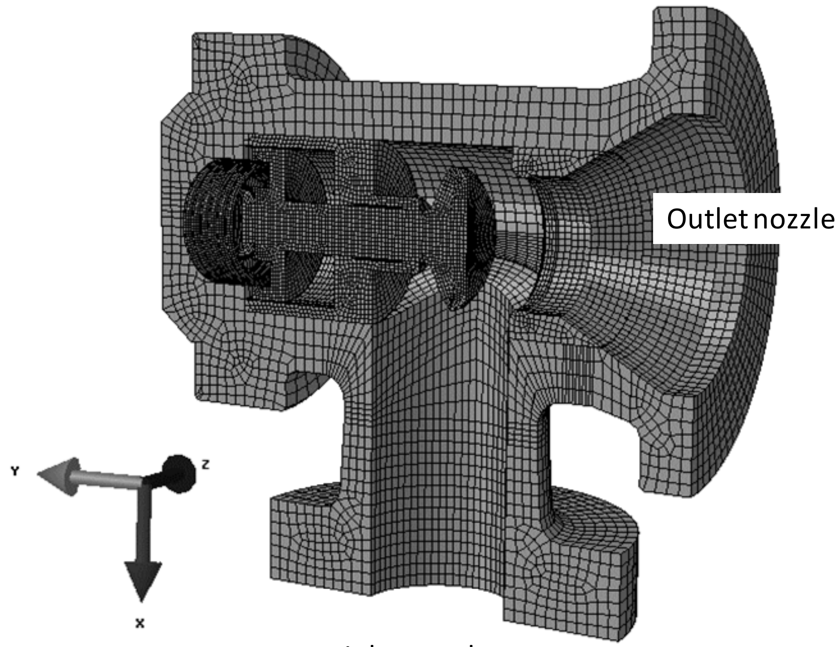

Figure 11. Orientations for mechanical boundary conditions

4.3 Stem to guide gap closure analysis

To provide for relative motion between the main valve stem and guide, the SRV is designed with an initial gap between the two components. The valve manufacturer has indicated that the dimensional value of this gap is proprietary. For the purposes of the current study, this uncertainty can be treated through a sensitivity study, and the time at which the gap is reduced to zero (corresponding to stem to guide binding) is calculated for a range of initial gap sizes.

In mechanical design, standard tolerances are provided for each type of clearance fit. Three types of clearance fit that likely bound the SRV stem-guide design are [8]:

- Loose running fit: for wide commercial tolerances or allowances on external members
- Free running fit: not for use where accuracy is essential, but good for large temperature variations
- Close running fit: for running on accurate machines and for accurate location at moderate speeds

For the three-stage Target Rock SRV nominal stem diameter of 50.8 mm, the corresponding minimum gap sizes are calculated according to the procedure given in [8] and presented in Table 3. These gap sizes are assumed to exist at SRV normal operating temperature of approximately 560 K.

Table 3. Minimum gap sizes for various clearance fit types for a nominal stem diameter of 50.8 mm

Clearance Fit Type	**Minimum gap size, mm**
Loose running fit	0.135
Free running fit	0.090
Close running fit	0.0275

The dimensions in Table 3 provide a threshold for main valve stem to guide binding, i.e. assuming an initial gap for each type of clearance fit, the time at which the stem expansion outpaces the guide expansion and reduces the gap to zero corresponds to valve binding (failure). Based on conversations with the valve manufacturer [9], the best estimate for the Target Rock three-stage valve corresponds to a free running fit.

4.4 Results

Figure 12 shows the temperature distribution (indicated in the legend by the ABAQUS variable NT11, corresponding to nodal temperatures) throughout the SRV at the final analysis time step for the 10% convective heat transfer flow condition. Thinner portions of the valve have less thermal mass, and experience a greater temperature increase. For the main valve stem, the region closest to the piston experiences the greatest heatup and thermal expansion.

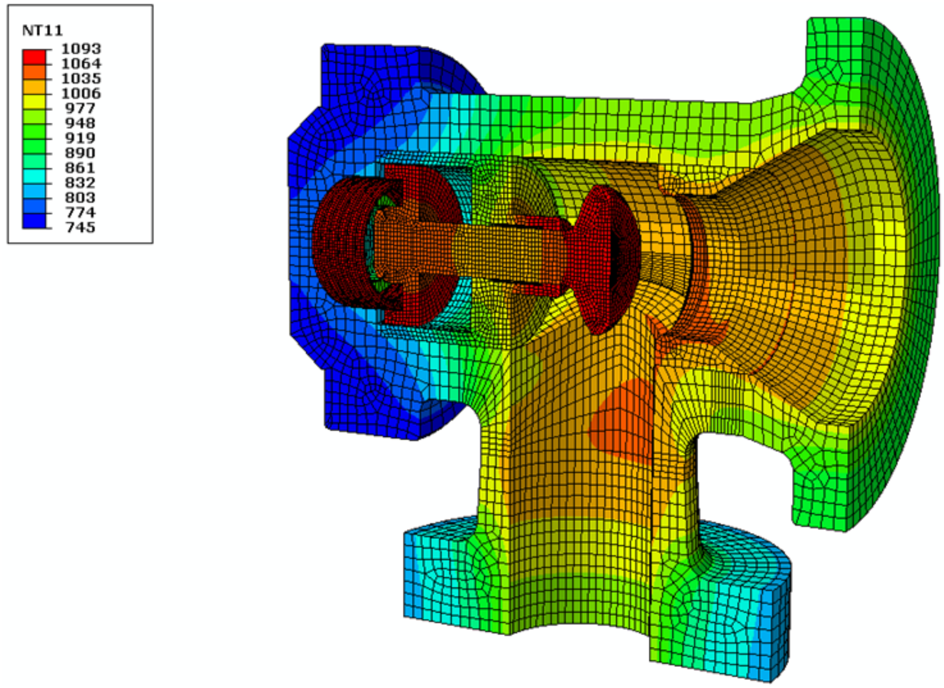

Figure 12. Nodal temperature distribution (Kelvin) throughout SRV at final analysis time step

Figures 13 and 14 show the main valve stem and guide thermal expansion, respectively, as a function of analysis time. Note that the analysis time begins ten hours after LTSBO initiation. Hence, the 6,000 seconds of analysis time in Figures 13 and 14 correspond to the 100 minute time interval between 600 minutes and 700 minutes in Figure 16 of [1], i.e. when the temperature excursion of the RCS becomes extreme. To account for the uncertainty in flow through the open space surrounding the main valve piston, the convective heat transfer coefficient in this region is varied as 5, 10 and 20 % of the full coefficient applied to the other portions of the valve experiencing full flow, i.e. from inlet nozzle directly to outlet nozzle.

As seen in Figures 13 and 14, both the guide and stem experience thermal expansion throughout the analysis. SRV seizure will occur if the gap between the guide and stem reduces to zero. Guide expansion increases the gap while stem expansion reduces the gap. Therefore, the gap as a function of time can be expressed in functional form as:

Gap = Initial minimum gap + Guide expansion - Stem expansion

With the initial minimum gap given in Table 3, and the time dependence of guide and stem expansion given in Figures 13 and 14, the gap time dependence can be calculated.

Figures 15, 16 and 17 show the calculated gap between the stem and guide for loose, free, and close running fits, respectively, as a function of analysis time. Included in each figure are the 5, 10 and 20% convective heat transfer flow assumption calculations.

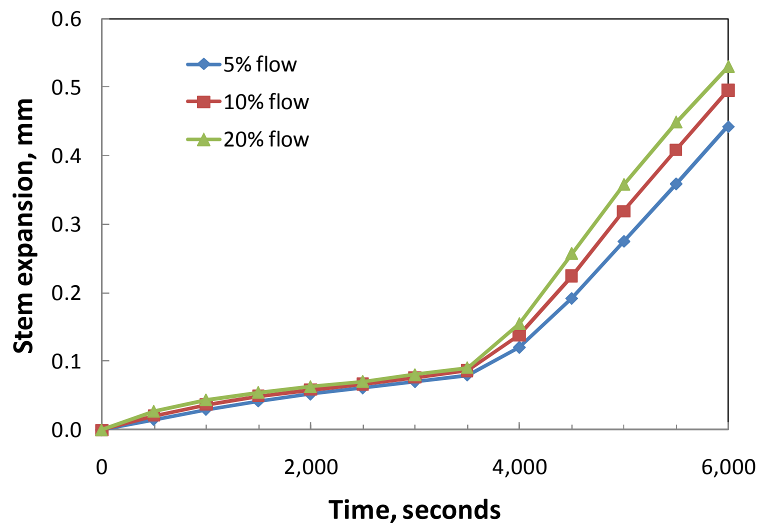

Figure 13. Maximum stem expansion vs. analysis time

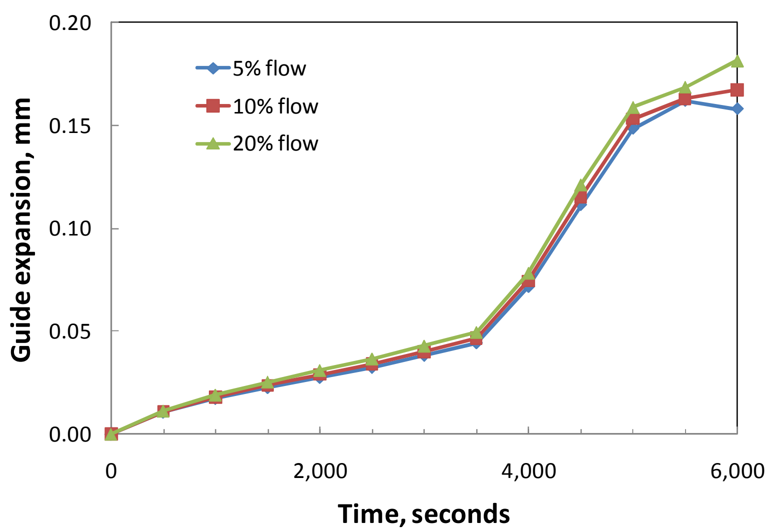

Figure 14. Guide expansion vs. analysis time

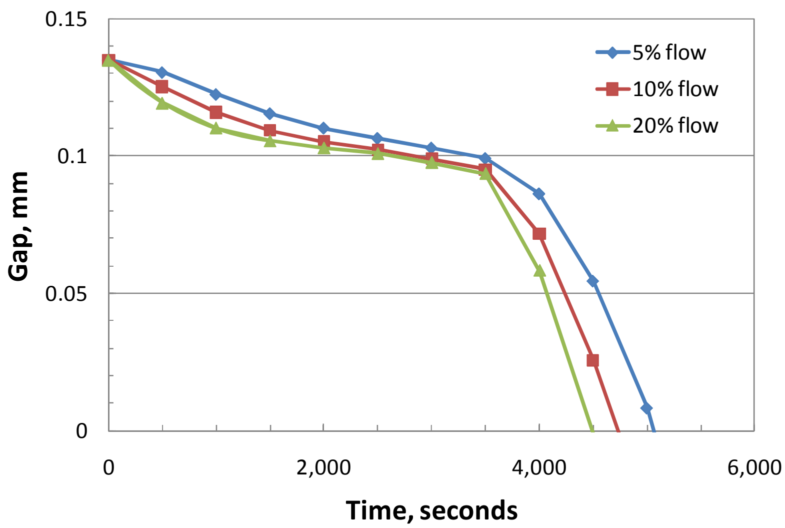

Figure 15. Gap vs. time for loose running fit

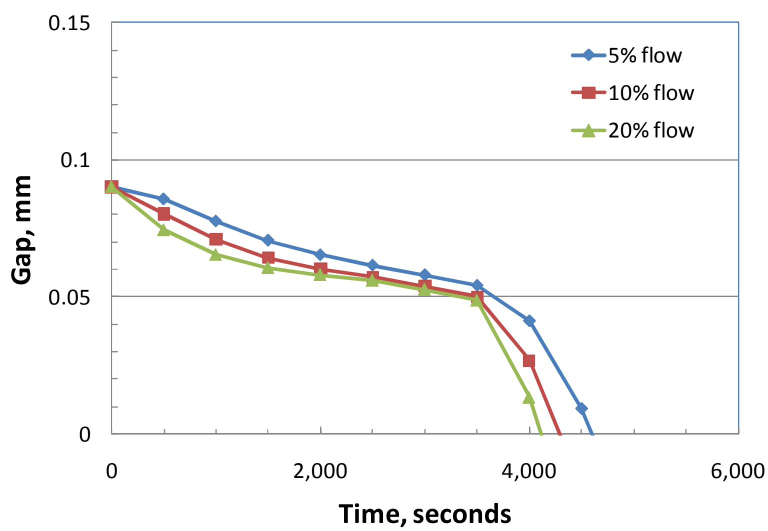

Figure 16. Gap vs. time for free running fit

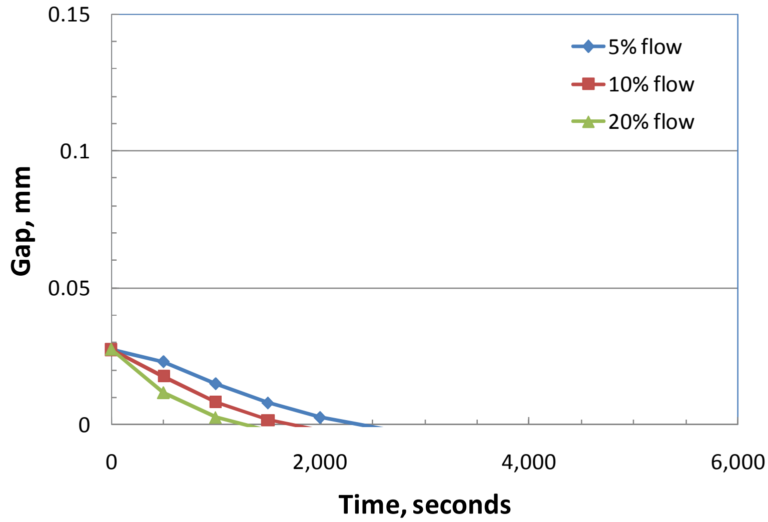

Figure 17. Gap vs. time for close running fit

For the loose and free running fits, the gap reduces to zero shortly after the time where main steam line temperature begins to increase at a high rate. For the close running fit, the initial gap is so small that it is reduced to zero upon relatively modest heating of the valve. Assuming the free running fit to represent the best estimate initial gap size, the times at which the gap reduces to zero for each convective heat transfer flow condition are linearly interpolated from Figure 16 and provided in Table 4. From these time values, the main steam line temperature at gap closure is linearly interpolated from the data in Figure 11 and Table 2 and provided in Table 4. Based on these calculations, it is estimated that the SRV will fail open roughly between 4,100 and 4,600 seconds (after the initial 10 hours of the LTSBO accident scenario), at a steam line temperature of approximately 800 to 900 K.

Table 4. Time and main steam line temperature at gap closure

Convective heat transfer flow condition	Time at gap closure (seconds)	Main steam line temp. at gap closure (K)
5%	4,602	902
10%	4,290	841
20%	4,112	806

4.5 Validation of Findings in SOARCA Report

In the SOARCA report [1], two analyses are presented that address thermal effects on valve reliability and performance. In the first analysis, thermal expansion is calculated due to differences in properties between the valve guide and stem materials, and an additional term is added that addresses the fact that the stem experiences a greater heat-up than the larger valve body. The result of these calculations presented in the SOARCA report gives a total stem to guide gap reduction of 0.0635 mm. If the initial minimum gap is reduced to this value, then the gap closure vs. time will occur as indicated in Figure 18. As seen in this figure, the time at gap closure is approximately 4,000 seconds corresponding to a main steam line temperature of approximately 800 K. These values are close to the range of times and main steam line temperatures calculated independently above.

In the second thermal analysis included in the SOARCA report, the effect of strength degradation of the valve stem material is analyzed. Based on strength reduction at elevated temperatures, an estimate of 900 K is given as the temperature at which the stainless steel stem will degrade to the point where the valve will fail. The 900 K valve stem temperature corresponds to a main steam line temperature of approximately 950 K [1]. In the current analysis, no direct mechanical loading of the valve components is applied. Hence, a direct comparison with the 900 K material failure criterion of the SOARCA report can not be made. The corresponding steam line temperature of 950 K is somewhat higher than the highest steam line temperature at failure (900 K) calculated in the current report. Sensitivity studies have been performed in SOARCA [1] that conservatively bound the results presented in the current study by a significant margin. While there is a temperature difference between the maximum steam line temperature at valve failure calculated in the current study and in SOARCA of 50 K, given that this temperature difference has been encompassed within sensitivity studies implies that conclusions obtained in SOARCA analyses performed to date remain valid.

In conclusion, the current analysis provides reasonable validation of the findings in the SOARCA report. Given the uncertainty inherent in such calculations of valve performance and reliability, the results calculated in the SOARCA report and in the current analysis are reasonably consistent, with variations addressed above. In the SOARCA report, the gap reduction calculated based on thermal expansions is estimated to be insufficient to cause valve failure. Given that the initial gap is unknown, a firm conclusion on this matter is difficult. However, in the current analysis, a method by which the time at gap closure can be estimated by varying the clearance fit type assumption. The best estimate in the current analysis is that the valve may fail open between approximately 4,100 and 4,600 seconds (after the initial 10 hours of the LTSBO accident scenario), at a steam line temperature of approximately 800 to 900 K. By comparison, the SOARCA report analysis calculates a valve failure criterion of 900 K with corresponding steam line temperature of (950 K) based on material degradation effects. Having addressed variations in steam line temperature at valve failure of a greater magnitude than the above difference, the valve failure criterion used in the SOARCA report is sufficient.

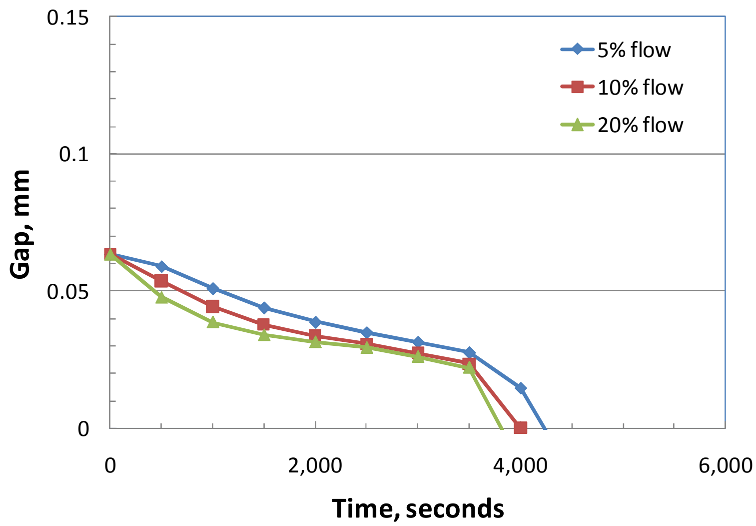

Figure 18. Gap vs. time for 0.0635 mm initial gap

5. Stochastic Failure

The SOARCA report [1] cites a plant-specific SRV re-closure failure rate provided in the Peach Bottom Individual Plant Examination of $3.7x10^{-3}$/demand. This failure rate is based on data from many individual valves that have been called upon to open (in service) and re-close one, or, at most, a few times. Operational events involving many SRV cycles have not been observed. In the SOARCA report, the mean number of cycles at which random SRV failure to re-close is expected to occur for a single valve is calculated as the inverse of the re-closure failure rate that is based on performance data from many valves. Specifically, the mean number of demands at failure is given by $1/3.7x10^{-3}$ = 270 demands, i.e. if 270 individual valves were called upon to open and re-close a single time, then, on average, one of them would fail to re-close. This data is used to infer that an individual valve called upon to open and close many times would fail to re-close, on average, on the 270th demand. Given that the valve internals may wear or degrade in each open/close cycle, the above basis for stochastic reliability is somewhat counter-intuitive.

An alternative basis for the SRV stochastic failure probability is proposed. An industry representative has stated that the valve manufacturer warrants the valves for hundreds of cycles at operating temperature and pressure conditions. Note that these conditions are to be expected throughout the initial time period of a LTSBO, up to approximately 10 hours during which the valve will be demanded to cycle approximately 400 times. The valve manufacturer has stated that laboratory tests have been performed to substantiate the conditions included in the valve warranty, i.e. that the valve can reliably open and close for hundreds of cycles. The industry representative also stated that fossil-fuel plant experience with the same types of valves can be used to validate these assertions.

In conclusion, the SRV re-closure failure rate assumed in the SOARCA report is reasonable. However, additional sources of reliability data exist that can provide a firmer basis for this value.

6. Potential Future Work

Specific failure mechanisms are postulated and analyzed in the SOARCA report [1] and in the current document for three-stage Target Rock SRVs. In light of the complex nature of the valves' operation, additional failure mechanisms and considerations may play a role in the performance and reliability, including:

- Failure of the pilot or intermediate stage
- Main valve spring fatigue failure following several hundred SRV operations
- Corrosion binding, wherein corrosion products accumulate on tight seating surfaces. This would likely cause the valve to fail closed, requiring additional pressure beyond setpoint to open the valve
- High temperature corrosion mechanisms beyond corrosion binding
- Modeling of connected piping system
- Inclusion of high temperature effect on valve action and spring force

Additional study beyond that contained in this document may provide greater insight into SRV behavior in accident conditions.

7. Summary

An independent analysis of the performance and reliability of a three-stage Target Rock safety relief valve in a LTSBO scenario for a BWR-4 with Mark I containment is presented. This analysis is quantitatively compared to the corresponding evaluation of this component included in a report of the SOARCA program [1] applied to the Peach Bottom nuclear power plant. In the current document, a detailed three-dimensional finite element analysis of major components of the valve is performed, with convective heat transfer from the main steam system applied. The analyses show reasonable agreement with the SRV stem to guide gap closure analysis (corresponding to valve seizure) presented in the SOARCA report. The time to valve seizure in the open position is estimated to be between 4,100 and 4,600 seconds (after the initial 10 hours of the LTSBO event) at a corresponding steam line temperature of approximately 800 to 900 K. The SOARCA report calculates valve seizure due to material degradation at a valve stem temperature of 900 K, corresponding to a main steam line temperature of 950 K. The result is that there is a difference in steam line temperature at failure calculated in the SOARCA report of 950 K and the maximum steam line temperature at valve failure of 900 K calculated in the current report. Sensitivity studies have been performed in SOARCA [1] that conservatively bound this temperature difference, and therefore this difference is believed to provide no deviation from the conclusions presented for SOARCA.

Separately, the SRV's stochastic failure to re-close is discussed. The expected value for the number of valve cycles to failure (270) used in the SOARCA study [1] is found to be reasonable. Additional physical basis for this value is provided in the current report.

8. References

1. State of the Art Reactor Consequence Analyses (SOARCA) Project, Appendix A, Peach Bottom Integrated Analysis, NUREG/CR–7110, Volume 1, Sandia National Laboratories.

2. ABAQUS User Manual, Simulia, Dassault Systems, version 6.10, 2010.

3. Licensee Event Report #50-366/1980-161

4. Licensee Event Report #50-333/LER-03-002

5. Industry Performance of Relief Valves at U.S. Commercial Nuclear Power Plants through 2007, NUREG/CR-7037, INL/EXT-10-17932, March 2011.

6. Target Rock Corporation Drawing Number 7467F-000, "Assembly 6x10 Pilot Operated Relief Valve"

7. Target Rock Corporation Drawing Number PL-7467F-000, "Parts List Assembly 6x10 Pilot Operated Relief Valve"

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9. Telephone conversation with Alex DiMeo of Curtiss-Wright Flow Control, Target Rock Division.